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Advanced Jupiter Probes

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Abstract

This Paper describes the results of new analyses and mission/system designs for low cost Advanced Jupiter Probes. Science and measurement objectives, instrumentation, entry probe design, and mission/system design options are described and reflect an aggressive approach to the application of new advanced technologies expected to be both available and developed over the next few years. The application of these new technologies have both reduced costs and increased science return compared to previous designs.

1. Introduction

Over the past two years a focused effort has taken place to define new low cost missions to explore the nature of Jupiter's atmosphere. This paper describes the results of this effort.

The extraordinary information returned by the Galileo Jupiter Probe stimulated new interest in Jupiter's atmosphere. This new information posed new and significant questions to our understanding of the unique system that is Jupiter's atmosphere, largest by volume and mass of any planet in our Solar System. The grand nature of this environment requires special attention in designing systems that will explore it. This paper describes the science requirements and measurement objectives leading to the system designs for the Advanced Jupiter Probes (AJP), as well as the technologies required to be incorporated in the system designs.

2. Science and Measurement Objectives

Two primary sources, the Solar System Exploration Roadmap (SSER, see the Reference) from NASA's Office of Space Science, and its science working group, the Astrophysical Analogs in the Solar System Campaign Science Working Group (AACSWG) suggest the broad science goals motivating the AJP mission. Relative to the SSER's priorities, the AJP mission attempts to (1) understand the raw materials and processes that formed Jupiter and the Solar System, and (2) understand current processes in Jupiter's atmosphere: how it "works" and how it is evolving. These address directly the SSER goals of understanding the origin of the solar system and the objects within it, and understanding the processes now occurring in planets, and how they are evolving. The AACSWG also sees in the AJP mission the means to gain sufficient knowledge about the composition of and processes occurring at Jupiter to allow using Jupiter as an analog for extrasolar giant planets and brown dwarfs.

These science goals are manifested in four high-priority science objectives. The science objectives are to understand:

1. Jupiter's composition, and the spatial variability of composition with depth and latitude
2. Jupiter's atmospheric structure (temperature, pressure, and density *vs.* depth) and its spatial variations
3. Jupiter's zonal flow structure and atmospheric circulation
4. Energy flow in Jupiter's atmosphere, and its effects on atmospheric dynamics

Entry probe missions are not the only source of information relevant to these objectives. In many cases, information from the entry probes works in concert with other forms and sources of information to yield an observational base sufficient to fulfill them. But for some objectives entry probes represent either the only way or the best way known to obtain critical information.

The data set needed to achieve these objectives calls for a suite of measurements, some of which entry probes would supply. Since the objectives address spatial variations, especially latitudinal variability, they naturally imply the need for multiple entry probes. The AACSWG determined that a desirable mission would sample three or more different latitudes in the ±25° range, including typical areas within both "belts" and "zones," preferably quasi-simultaneously. They established measurement priorities in two different depth ranges, the "shallow" range with pressure levels from 0.1 to ~20 bars, and the "deeper" range from ~20 to ≥100 bars. Within the shallow range, the highest priorities are:

1. Mixing ratios of the primary bearers of C, O, N, and S, such as CH_4, NH_3, H_2O, and H_2S, and their variations with depth
2. Detection and characterization of clouds (i.e., cloud density, particle sizes, etc.) due to the species in (1.) and their reaction products, such as NH_4SH
3. Atmospheric structure: temperature, pressure, and density *vs.* depth
4. Bulk flow velocity (wind) *vs.* depth
5. Vertical radiant energy flux, including sunlight penetration, *vs.* depth
6. Ortho- to para-H_2 ratio
7. Noble gas and disequilibrium species (such as CO) abundances, and isotopic ratios for selected species

A sampling resolution of at least six samples per atmospheric scale height is desired in this shallow range. Some of these measurements, such as sunlight penetration, are applicable only to the shallow range. Others assume lower priorities within the deeper range. Within the deeper range, only three of these measurement objectives retain high-priority status:

1. Atmospheric structure: temperature, pressure, and density *vs.* depth
2. Bulk flow velocity (wind) *vs.* depth
3. Mixing ratios of diagnostic species (such as H_2O and CO) *vs.* depth

Within this range the sampling resolution can be relaxed to only two per scale height.

The Galileo Probe has already made some measurements, such as the bulk He/H_2 ratio, that have been deleted from earlier versions of these high-priority measurements lists. That probe was certainly an excellent start toward understanding Jupiter's atmosphere, but its penetration depth limitation and unfortunate entry into a distinctly non-representative region of Jupiter's atmosphere underscore the need for follow-on, multiple-probe missions.

3. Instrumentation

A suite of at least five and possibly six instruments is needed to perform the measurements described above. Of the payload suite the Gas Chromatograph /Mass Spectrometer is (GCMS) the major system design driver - it requires an order of magnitude more mass, volume, and power to return the required composition data than all the other instruments together. The Galileo Probe mass spectrometer weighed about 20 kg; our advanced design GCMS could approach 5 kg. Availability will depend on funding, but could be ready just after the turn of the century.

Table 3.1 gives the envisioned instrument complement and the measurements performed by each. Measurement accuracies are not yet fully determined, though for most investigations the accuracies of analog Galileo Probe instruments are sufficient.

Instrument	Measurements Performed
Gas Chromatograph / Mass Spectrometer (GCMS)	Composition, constituent mixing ratios; Isotopic ratios
Nephelometer	Cloud density
Atmospheric Structure Package (ASP): thermometers, barometer, accelerometers	Atmospheric temperature, pressure, and density; winds
Net Flux Radiometer (NFR)	Vertical radiant energy flux
Sound Speed Instrument	Ortho- to para-H_2 ratio (inferred)
Ultrastable Oscillator (USO) ?	Winds, via a Doppler Wind Experiment (DWE)

Table 1. Instrument complement and measurements performed by the AJP payload.

The Doppler Wind Experiment (DWE) is not wholly redundant with the ASP wind investigation. ASP wind measurements depend on integration of data from the onboard accelerometers. The errors, and thus the uncertainties, associated with such integrations grow with time. At the deeper levels, late into the entry mission, uncertainties may grow so large they compromise the usefulness of the measurements. DWE uncertainties do not grow with depth, and in fact can diminish with depth for some relay geometries. If ASP wind measurement uncertainties exceed science requirements at the deeper levels, a DWE, and thus a USO, may be required.

Mission requirements place rather strict constraints on the payload's mass, volume, power consumption, and telemetered data rate. In all cases use of Galileo Probe instruments would violate the constraints, so a significant instrument development effort is needed. Instrument data rates, especially for the GCMS, require high data compression ratios to fit practical telemetry rates, but the Galileo Probe mission faced this same problem. Design engineers studying the AJP mission already envision data compression schemes that can meet the link requirements for at least some mission designs, without sacrificing science objectives. Techniques for reducing the mass, power, and volume of the instruments are much more uncertain. For the studies to date those figures are rough estimates, so they are more a representation of goals for the development programs. The current Deep Probe design allocates 8 kg and 18 Watts to the total instrument payload.

4. Entry Probe Design and Technology Drivers

Surviving entry into Jupiter's atmosphere from a hyperbolic approach is difficult. The Galileo Probe successfully achieved this goal, making maximum use of Jupiter's rapid rotation to mitigate the entry speed. But the budget for development of the Galileo Probe alone is more than the budget goal for an entire AJP mission project. At Galileo Probe cost levels, no further giant planet probe missions would be flown in the foreseeable future. AJP mission studies aim at finding means of implementing AJP missions with costs that allow pursuing them on the SSER's schedule.

Multiple design drivers constrain our options for achieving the AJP science and mission cost goals. The payload carries some drivers, such as the data volume needed to meet measurement objectives and reasonable mass and power for the instrument complement. Probe subsystems also have strong drivers, including the Data Handling and Power subsystems and particularly the Thermal and Telecommunication subsystems.

Thermal design is a major factor in a deep Jupiter probe design. Surviving entry requires that a large fraction of the probe mass be the entry Thermal Protection System (TPS), consisting of a massive ablative heat shield and a smaller but still substantial backshell. The Galileo TPS was fully 50% of the entire probe's mass. Technological advances that can decrease the needed TPS mass fraction have significant beneficial effects: they can greatly increase the science return if the probes are mass-constrained, or they can greatly decrease a probe's mass (and thus total mission cost) for a given minimum science return. New knowledge about aerothermodynamic behavior and heat shield response gained from Galileo Probe entry data, if properly analyzed and applied, might reduce that mass fraction to ~ 45% (Paul Wercinski, private communication). Further research into the aerothermodynamics and new heat shield materials might push that to as little as 35%, but with a major R&D effort. In a cosmic Catch-22 situation, attaining the 35% figure itself may require new jovian entry probe data, because laboratory hypersonic wind tunnels that address aerothermodynamics simply cannot approach the extreme Mach numbers of jovian entry.

A second, sometimes surprising facet of Jupiter probe thermal designs is the high temperature environment deep in Jupiter's atmosphere. Although Jupiter's tropopause is far colder than any of the inner planets', the jovian atmosphere's great depth and the natural increase in temperature with tropospheric depth combine to yield temperatures surpassing even Venus' surface. The Galileo Probe mission terminated at the 23 bar level due to temperatures between 400 and 500 K, not due to pressure. At the 100 bar level, Jupiter is only ~50-60 K cooler than Venus' 730 K surface. Any descent module exposed to these conditions for more than a few minutes must have some means of thermal protection.

Telemetering the probes' data is a non-trivial problem. The volume of data a telecommunications system can relay depends primarily upon five factors: (1) transmitter power; (2) transmit and receive antenna gains and beam patterns; (3) extinction (absorption or scattering) of the radio signal by intervening material, in this case Jupiter's atmosphere; (4) time available for relay; and (5) distance between the transmitting and receiving antennas. In general,

$$V_D = \int_0^{t_R} R_D dt \approx \int_0^{t_R} R_0 \frac{P_T G_T G_R (1-E)}{D^2} dt \tag{1}$$

where V_D is the relayed data volume, R_D is the instantaneous data rate, R_0 is a proportionality constant, P_T is the transmitted power, G_T and G_R are the instantaneous transmitting and receiving antenna gains, respectively, considering their beam patterns and the signal direction, E is the fraction of the signal's power absorbed or scattered, D is the distance between antennas, and t_R is the time available for relay. Values for the parameters in the rightmost integral are not freely variable, but are subject to physical constraints. Transmitter power is tied to available electric power, with a mass penalty for increases. For a given wavelength, antenna gain is roughly proportional to aperture (area), but beam width is inversely proportional to antenna diameter, so increasing the gain narrows the beam width. Because the carrier/relay spacecraft (CRSC) can be significantly away from the probe's zenith, and because atmospheric turbulence causes quasi-unpredictable swinging by the probe, there are lower limits to the transmitting antenna's beam width. This places rather low upper limits on that antenna's gain. For small probes there is another potential limit to antenna gain: the antenna cannot be larger than the descent module dimensions. There are practical limits also to the mass and size, and thus the gain, of the receiving antenna on the CRSC. Mission design constraints dictate lower limits for D. These limits set an upper limit to the practical data rate available to a mass-constrained entry probe. Given the low limits on P_T and G_T, and the relatively large values of D in the jovian system, that rate is fairly low: on the order of 200 bps for the most advantageous mission designs considered, and only at shallower levels. This is considerably slower than the combined instrument data rates at the prescribed sampling intervals, so data compression is a necessity.

At radio frequencies the extinction factor is significant in Jupiter's atmosphere and increases with depth, mostly due to ammonia and water vapors. In jovian environmental conditions and at typical spacecraft communications frequencies the log-scale absorptivities of those species are roughly proportional to frequency squared, driving the link design toward lower frequencies. But Jupiter and its radiation belts place lower limits on usable link frequencies from their intense synchrotron emissions, which at frequencies too far below ~1 GHz overwhelm the signal with synchrotron noise. These design studies used a 900 MHz link.

To a lesser extent than the Thermal and Telecommunications subsystems the Power and Data Handling subsystems are also design drivers. The Data Handling subsystem must have the compute power to perform the required data compression tasks, control various actuators and deployments and possibly sampling schedules, and store data for relay. The Power subsystem must power all the probe systems, and in general as they become more capable, the Power subsystem becomes larger. For probe mission durations of one or two hours the best solution appears to be primary batteries. Battery chemistry is an obvious trade parameter, but for Jupiter entry probes so are structural characteristics, because the batteries must survive decelerations of hundreds of gees. Fortunately, appropriate battery designs do not require battery technologies beyond current plans. The main design driver for battery sizing is discharge rate, not capacity, so there is ample surplus capacity to run a "wake-up" timer that activates the probe upon approach to Jupiter.

In all cases the probe design takes advantage of the technology advances in miniaturization of subsystems, particularly in the integration of electronics. Packaging requirements have been reduced, allowing significant reductions in mass and volume. AJP design has made good use of the available miniaturization technology that is continuing to be developed.

Two types of probes were designed in the JPL studies: one to achieve deep 100-bar penetration of the Jupiter atmosphere, the other acting primarily as a technology flight test bed for the entry shield and reaching 10 to 20 bars. The 100-bar probe objective is science return; the goals are as outlined in Section 2 with composition as a major objective. The deep probe design, exclusive of entry shield, weighs about 50 kg.

A small team at JPL led by Henry Harris designed the smaller technology probe; Paul Wercinski of Ames Research Center was an active member of this team and provided aerothermodynamics expertise in designing the probe and a test program. The entire small probe masses about 15 kg, including its instrumented heat shield. Planetary science is included on a "space available" basis and confined primarily to pressure, temperature, and wind measurements.

5. Mission/System Design Options

Delivery of Jupiter Probes via a number of options has been studied. In particular, delivery through addition of probes to the NASA Outer Planets Exploration Program missions is of great interest because of their importance in the Solar System Exploration Strategic Plan and the potential low additional cost of such options. There are three missions in this Program:

- Europa Orbiter, scheduled for launch in 2003
- Pluto/Kuiper Express (PKE), scheduled for launch after 2003
- Solar Probe, scheduled for launch after 2003

The potentials of these missions for delivering atmospheric exploration Probes to Jupiter, in addition to carrying out their basic missions, are discussed below. First, however, the option for delivery of Jupiter Probes with a dedicated carrier/relay spacecraft (CRSC) is described.

5.1 Dedicated Carrier Delivery

Delivery of probes to Jupiter via a dedicated carrier, i.e., a mission designed for the sole purpose of Jupiter Probe delivery, is the baseline to which all other options must be compared, because the cost/benefit/risk of this baseline can be optimized without concern for any other mission requirements.

Studies over the past year performed at JPL analyzed a number of dedicated carrier/relay options. Some of the key trade parameters addressed in those studies are number and type of atmospheric entry probes, trajectory type, launch vehicle capability/cost, and advanced technology capabilities (e.g., entry heat shield, probe payload, and micro-system technologies). Two baseline options were studied in some detail:

- 3-Deep Probe delivery via Delta III Launch Vehicle (on ΔVEGA trajectory)
- 2-Deep Probe delivery via Delta II (7925H)/Star 37BP (on direct trajectory)

The 3-Deep-Probe option is attractive from the standpoint of near simultaneous delivery to three diverse locations within the ± 25-deg latitude band of interest. The Probes relay their data back to the carrier/relay spacecraft in a serial manner, one after the other. Figure 1 below illustrates the encounter profile design.

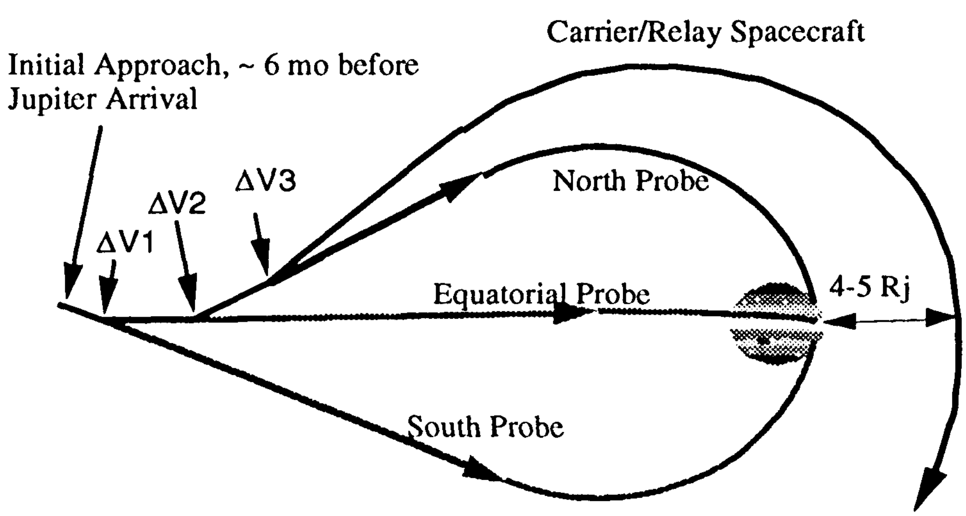

Figure 1. 3-Probe Delivery - Jupiter Encounter; View from Earth (not to scale)

A longer flight time and higher-cost launch vehicle than might be desired are required to deliver three Deep Probes to Jupiter: a 4.6-year flight on a ΔVEGA type trajectory (using a single Earth gravity-assist), launching from a Delta III (estimated cost of about $90 M). The probe descents are in daylight and are relatively slow for the desired sampling strategy. Advanced entry heat shield technology is required to enable this option, reducing the Galileo Probe's 50% heat shield mass ratio to 35%. This technology advance could delay launch beyond 2003. Advances in both systems and instrument micro-miniaturization are needed as well.The total mission cost for the 3-Deep Probe/Dedicated CRSC option is about $350 M, putting it just over the Discovery-class mission cost cap of about $300 M.

With one less Deep Probe delivered, the 2-probe option is nevertheless attractive from the standpoint of lower cost and half the flight time for delivery to Jupiter: a 2.3-year flight time on a direct trajectory, launching from a Delta II 7925H/Star 37 (estimated cost of about $65 M). The probe descent profiles and advanced technologies required to enable this option mirror those of the 3-probe option. The total mission cost for the 2-Deep-Probe/Dedicated CRSC option is about $250 M, putting it within the Discovery-class mission cost cap of about $300 M.

5.2 Europa Orbiter Delivery

The first scheduled Outer Planet Exploration Program mission is the Europa Orbiter. Current design of this mission will not permit delivery of any probes into the Jupiter atmosphere. Probe delivery scenarios were investigated: delivery on Jupiter approach before orbit insertion and delivery from Jupiter orbit. In both cases the mass margin would not permit carrying any probes.

5.3 Pluto/Kuiper Express Delivery

Another Outer Planet Exploration Program mission is the Pluto/Kuiper Express (PKE), with a potential launch as early as December of 2004. Current design of this mission will permit delivery of probes into the Jupiter atmosphere. One Deep Probe can be added to the PKE mission if it selects the STS/IUS launch vehicle, the same launch vehicle selected for the Europa Orbiter mission. No probe delivery is possible with the Delta II launch vehicle.

The encounter design for delivery of a single probe by the PKE mission allows delivery similar to the equatorial probe design of the three-probe delivery by a dedicated carrier/relay spacecraft, described above, i.e., prograde delivery but with two or more hours of relay link. Unfortunately probe entry takes place on Jupiter's nightside so the Net Flux Radiometer investigations are lost.

Addition of a probe to the PKE mission is contingent on development of heat shield and/or instrument technology. For a 45% heat shield mass ratio, an advanced 45-kg deep probe would be deliverable (the total probe mass would be 82 kg, i.e., a 45-kg probe with a 37-kg heat shield). Some science might be lost with this smaller deep probe - a probe design of 50 kg is currently considered feasible for the descent measurements desired . If advances in heat shield technology permitted a 35% heat shield mass ratio, then the 50-kg Deep Probe could be delivered by the PKE mission.

The deep probe was integrated into the PKE spacecraft design, placing the probe on the top of the PKE spacecraft system. A total integrated system design yielded the mass available for the probe and provided a cost estimate. The total additional mission cost for the addition of a single deep probe is about $100 M. This includes not only the cost of the probe, but also the additional development and operations costs.

5.4 Solar Probe Delivery

A third Outer Planet Exploration Program mission is Solar Probe, to launch after 2003. Current mission design with the Delta II launch vehicle will not permit the addition of probes for delivery into the Jupiter atmosphere. Probes can be added to the Solar Probe mission if a more capable (and more costly) launch vehicle is selected. Studies of a Solar Probe mission launched from an Atlas 2ARS launch vehicle (about $105 M) indicate that at least one 50-kg Deep Probe (with 45% heat shield mass ratio technology) can be integrated for Jupiter delivery. If heat shield mass ratios can be reduced to 35% through aggressive technology development, then it would be possible to deliver two 50-kg deep probes. The total additional cost for this 2-probe option would be about \$190 M, including the extra cost to select a launch vehicle of higher performance. Figure 2 illustrates the encounter profile for delivery of a single probe by the Solar Probe mission.

A total integrated system design study, integrating the Deep Probes into the Solar Probe spacecraft design, yielded the mass available for the probes and provided a cost estimate. The Probes are placed in a separate module along the axis of the Solar Probe spacecraft. The total additional mission cost for the addition of two deep probes is about \$190 M. This includes not only the cost of the probes, but also the additional development, operations costs, and upgraded-performance launch vehicle (Atlas 2ARS).

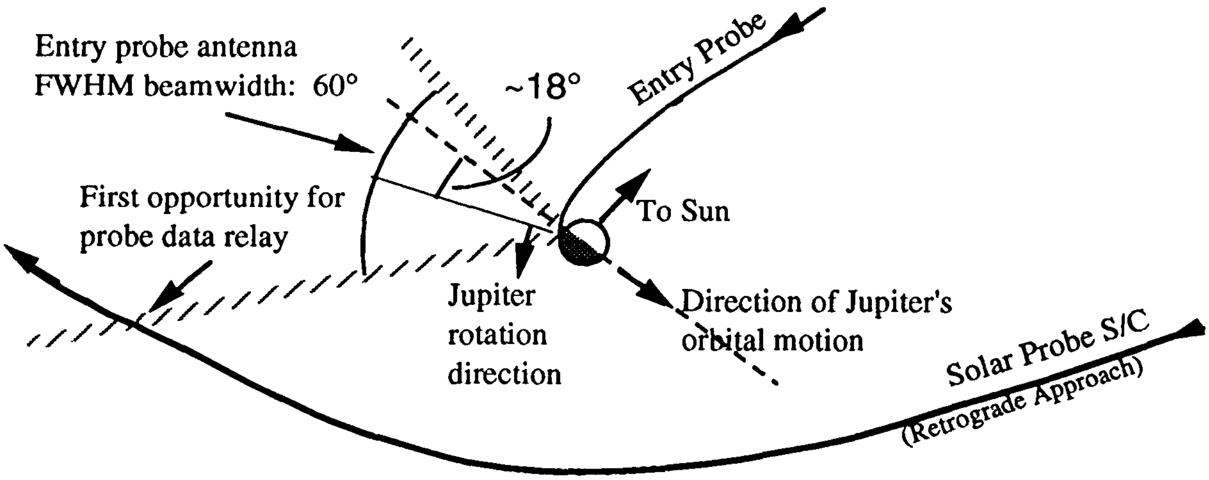

Figure 2. Solar Probe Delivery of single Jupiter probe - Jupiter Encounter

5.5 Mission/Systems Design Options Summary

Table 2 below summarizes the mission delivery options. Note that two or three small technology probes could replace a single deep probe, but significant composition science data would be lost.

Delivery Mission	Desired Probe Mix (Launch Vehicle)	Science	Advanced Technology Needs	Δ Cost of Probe(s) Mission
• Pluto/ Kuiper Express	Single adv 45-kg Probe {45% Heat Shield mass ratio} (STS/IUS)	• Single Deep 45-kg Probe one entry site (±25°) • Nightside Entry • 5 to 10 deep composition samples from 1 probe	• Reduced mass for instrument support **or** • 35% TPS M/R (Launch > 2003)	\$100 M {1 Probe}
• Europa Orbiter	None (STS/IUS)	N/A	N/A	N/A
• Solar Probe	Two 50-kg Probes {35% Heat Shield mass ratio} (Atlas 2ARS/ Star 48)	• Two Deep 50-kg Probes (two entry sites at ± 10°) • Nightside Entry • < 1 deep composition sample from each probe	• 35% TPS M/R (Launch > 2005)	~ \$190 M {2 Probes}
• Dedicated Carrier/ Relay S/C	Two 50-kg Probes {35% Heat Shield mass ratio} (DII-7925H/ Star 37BP)	• Two Deep 50-kg Probes (Two entry sites at ± 25°) • Daylight Entry • ~ 5 deep composition samples from each probe	• 35% TPS M/R • Micro-Systems (Launch > 2005)	\$250 M {2 Probes}

Table 2. Mission/System Design Options Summary

6. Conclusion

The Galileo Probe explored Jupiter's atmosphere to a depth of about 20 bars and found what scientists feel was an anomalously water-deficient region. Their desire is to return to Jupiter with lower cost probes that allow entry into multiple sites and to depths of 100 bars or more.

Modest technology development of the probe entry shield is possible based on the Galileo Jupiter Probe experience. Without a Jupiter flight test, however, the Galileo shield mass ratio can most likely be reduced by only a small amount, to about 45%.

Miniaturization of both probe engineering support systems and payload instruments allows greater penetration depths at lower cost and the possibility of delivery by other missions already targeted for Jupiter. Spacecraft dedicated to delivery of just the Jupiter Probes are also possible with lower cost launch vehicles and allow delivery of more than one probe.

7. Acknowledgment

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8. Reference

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